

Chapter 2

Definitions and Effects

2-1. Radioactivity

a. General information

(1) Nuclear processes. Radioactivity is the process in which an unstable nucleus of an atom decays to a more stable state, with a lower energy level, and radiates energy in the process. This energy is the energy difference between the unstable and stable nuclear states and is emitted as either particles with kinetic energy, such as alpha particles (two protons and two neutrons), beta particles (electrons), neutrons, or photons (gamma rays). These types of radiation are called ionizing radiation because the energetic particles or rays which are emitted have enough energy to, directly or indirectly, eject orbital electrons from atoms or molecules, thereby converting them to positive ions.

(2) Natural radioactivity. Many elements in the earth's crust are naturally radioactive, and others are made radioactive (unstable) by being exposed to radiation (energy) from another source. Some elements exist naturally in different forms, known as isotopes, each with the same number of electrons and protons, but with different numbers of neutrons in the nucleus. An example is hydrogen, with the stable ^1H and the unstable (radioactive) ^3H , which decays to stable ^3He with the emission of an electron.

(3) Beta decay. Tritium is an example of beta decay, in which an ordinary electron is ejected from the nucleus of an unstable atom. The electron is formed when a neutron transforms into a proton. Beta decay occurs among isotopes with a surplus of neutrons. Another example of beta decay is the decay of Cobalt-60 to Nickel-60 with the emission of beta particles and gamma rays.

(4) Alpha decay. An alpha particle is a positively charged assembly of two protons and two neutrons. This configuration is identical to the nucleus of the helium atom. An alpha particle is emitted from the nucleus of a radioactive isotope when the neutron-to-proton ratio is too low, and this occurs mainly in elements with atomic numbers greater than 82 (lead). An example of alpha decay is the decay of Uranium-235 to Thorium-231, which produces an alpha particle and gamma rays.

(5) Gamma decay. A photon (gamma ray) is emitted in gamma decay, which typically accompanies both beta and alpha decay, as is shown in the examples above.

(6) Activity. The traditional unit for the activity, or rate of decay, of a radioactive material is the curie (Ci), which is 3.7×10^{10} disintegrations per second (dps). The modern Systeme Internationale d'Unites (SI) unit is the becquerel (Bq), which is equivalent to 1 dps. It is impossible to predict when a given single unstable atom will decay. It is a random process. However, each isotope has a certain tendency to decay, depending on how unstable it is. The overall average rate of decay of a large mass of an isotope containing billions and billions of atoms can be measured.

(7) Activity equations. The rate of decay of unstable atoms is proportional to the number of unstable atoms present, so a given fraction of the total unstable atoms of the mass will decay in a given time period. Thus,

$$N_t = N_0 e^{-\lambda t} \quad (2-1)$$

where

N_t = number of unstable atoms of the isotope present after time, t (unitless)

N_0 = initial number of unstable atoms of the isotope (unitless)

λ = decay rate constant (1/time)

t = time (time can be in any units as long as they are consistent)

(8) Half-life. The fact that radioactive decay is proportional to the number of unstable atoms present means that first-order kinetics hold, and an exponential rate can be used to describe it. The relationship most commonly used is the concept of half-life. Since certain fractions of a given isotope always decay in a given time, one half of a mass of an isotope always decays in the same time, no matter how much is present. This time is called the half-life. It varies from isotope to isotope and ranges from instantaneous to millions of years. The half-life is $0.693/k$, where k is the decay rate constant (0.693 is the ln of 2).

Example:

If a mass of an isotope has a half-life of 10 years and an activity of 64 Bq at time zero, the activity will be as follows:

32 Bq in 10 years
16 Bq in 20 years
8 Bq in 30 years
4 Bq in 40 years
2 Bq in 50 years
1 Bq in 60 years

b. Units and measurements.

(1) Dosimetry. The ionizing radiation from a radioisotope can damage living tissue. Thus, a system has been devised to measure and quantify the radiation that interacts with tissue. This system is known as radiation dosimetry and involves the quantities of exposure, absorbed dose, dose equivalent, and effective dose equivalent.

(2) Exposure. Exposure is defined as the amount of x- or gamma radiation absorbed per unit mass of air. Radiation is measured by electric charge per unit mass, Coulombs (C) per kilogram of air. There is no SI unit for exposure. The unit formerly used for exposure is the Roentgen (R), which is equivalent to 2.58×10^{-4} C/kg air (88 ergs/gin).

(3) Absorbed dose. The absorbed dose is the mean energy imparted by ionizing radiation per unit mass of material. The SI unit for absorbed dose is the gray (Gy), which is equal to an absorbed dose of 1 Joule/kilogram (100 rads). The rad (radiation absorbed dose) was previously used as a measure of the dose of any ionizing radiation to the body tissues in terms of the energy absorbed per unit of mass tissue. One rad is the dose corresponding to the absorption of 100 ergs/gin of tissue.

(4) Quality factor. Biologically, the type of radiation is important as well as the amount. Each type of ionizing radiation has an associated quality factor (Q) which describes the rate at which the emitted particle deposits its energy when traveling through matter. Thus, the quality factor is a modifying factor for the amount of ionization produced by a given amount of each type of ionizing radiation. An alpha particle is large, heavy, and doubly charged, and it deposits its energy quickly. Therefore, it is assigned a quality factor of 20. Gamma rays (including x-rays) and beta rays are assigned a quality factor of 1.

High-energy protons and neutrons of unknown energy both have a quality factor of 10. These factors are summarized in Table 2-1.

Table 2-1
Quality Factors and Absorbed Dose Equivalences

Type of Radiation	Quality Factor Q	Absorbed Dose Equal to a Unit Dose Equivalent ¹
X-, gamma, or beta radiation	1	1
Alpha particles, multiple-charged particles, fission fragments and heavy particles of unknown charge	20	0.05
Neutrons of unknown energy	10	0.1
High-energy protons	10	0.1

¹Absorbed dose in rad equal to 1 rem, or the absorbed dose in gray equal to 1 sievert. Source: 10 CFR 20 (Federal regulations are listed in Appendix B, Section B-3, "Bibliography of Regulatory Documents.")

(5) Dose equivalent. The dose equivalent (H_T) is the product of the absorbed dose in tissue in rads or grays (D), quality factor (Q) (unitless), and all other necessary modifying factors at the location of interest (N) (unitless). The dose equivalent can be represented by the following equation:

$$H_T = DQN \quad (2-2)$$

The special unit for dose equivalent is the rem, roentgen Equivalent man, which is equal to the absorbed dose in rads multiplied by the quality factor and other modifying factors.

The rem is a measure of the dose of any ionizing radiation to body tissues in terms of its estimated biological effect relative to a dose of one roentgen of x-rays. The SI unit is the sievert (Sv) which is equal to the absorbed dose in grays multiplied by the quality factor and other modifying factors ($1 \text{ Sv} = 100 \text{ rems}$).

(6) Committed, deep, and eye dose equivalents. The committed dose equivalent ($H_{T,50}$) means the dose equivalent to organs or tissues of reference (T) that will be received from the intake of radioactive material by an individual during the 50-year period following the intake. The deep-dose equivalent (H_d), which applies to external whole-body exposure, is the dose equivalent at a tissue depth of 1 cm ($1,000 \text{ mg/cm}^2$). The shallow-dose equivalent (H_s), which applies to external exposure

of the skin or an extremity, is taken as the dose equivalent at a tissue depth of 0.007 cm (7 mg/cm^2) averaged over an area of 1 cm^2 . Eye-dose equivalent applies to the external exposure of the lens of the eye and is taken as the dose equivalent at a tissue depth of 0.3 cm (300 mg/cm^2).

(7) Effective dose equivalent. Different organs have differing sensitivities to radiation. The effective dose equivalent (H_E) is the sum of the products of the dose equivalent to an organ or tissue in rem or Sv (H_T) and the weighting factors (W_T) applicable to each of the body organs or tissues that are irradiated.

$$H_E = \sum W_T H_T \quad (2-3)$$

Effective dose equivalents have the same units as dose equivalents which are Sv and rem.

(8) Committed and total effective dose equivalents. The committed effective dose equivalent in rem or Sv ($H_{E,50}$) is the sum of the products of the weighting factors applicable to each of the body organs or tissues that are irradiated and the committed dose equivalent to these organs or tissues.

$$H_{E,50} = \sum w_T H_{T,50} \quad (2-4)$$

The total effective dose equivalent (TEDE) in rem or Sv means the sum of the deep-dose equivalent (for external exposures) and the committed effective dose equivalent (for internal exposures).

$$TEDE = H_d + H_{E,50} \quad (2-5)$$

(9) Weighting factors, maximum TEDEs, and units. The organ dose weighting factors can be found in Table 2-2, and the maximum effective dose equivalents can be found in Table 2-3. Table 2-4 is a summary of the units explained in the previous discussion. The International Commission on Radiation Protection (ICRP) has recommended new limits and definitions for the values discussed above in the ICRP 60 publication (ICRP 1990). These values have been indicated in parentheses.

c. Effects of radiation exposure.

(1) Direct and indirect effects. Ionizing radiation may affect the human body either directly, by ionizing

Table 2-2
Organ Dose Weighting Factors

Organ or Tissue	W_T^1	ICRP 60
Gonads	0.25	(0.20)
Breast	0.15	(0.05)
Red Bone Marrow	0.12	(0.12)
Lung	0.12	(0.12)
Thyroid	0.03	(0.05)
Bone Surfaces	0.03	(0.01)
Colon ²		(0.12)
Stomach ²		(0.12)
Bladder ²		(0.05)
Liver ²		(0.05)
Oesophagus ²		(0.05)
Skin ²		(0.01)
Remainder (no more than 0.06 for any single organ)	0.303	(0.05) ⁴
Whole Body	1.005	

¹From 10 CFR 20, dated January 1, 1993.

²These organs are not assigned separate tissue weighting factors under 10 CFR 20.

³0.30 results from 0.06 for each five "remainder" organs (excluding the skin and lens of the eye) that receive the highest doses.

⁴The remainder is composed of the following additional tissues and organs: adrenals, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus, and uterus.

⁵For the purpose of weighting the external whole body dose, a single weighting factor, $W_T = 10$, has been specified. The use of other weighting factors for external exposure will be approved on a case-by-case basis until such time as specific guidance is issued.

atoms or molecules, or indirectly, by the production of free radicals and hydrogen peroxide in the water of body fluids. The direct effect is the mutation of a cell, while the indirect effect is toxicity from the free radicals. Thus, the damage from radiation overexposure can manifest itself in numerous ways.

(2) Acute and chronic doses. Effects from overexposure also depend upon the amount and length of exposure. An acute exposure is a single exposure to a high dose of radiation in a short period of time. Biological effects from an acute exposure will appear relatively soon for doses greater than 50 rems. A chronic exposure is a repeated or prolonged exposure so as to lead to a cumulative effect, and the effects may not be apparent for years.

Table 2-3
10 CFR Dose Limits

1. Occupational

A. Annual limit (more limiting 09.

1. Total effective dose equivalent of 5 rems (0.05 Sv), or
2. Sum of deep-dose equivalent and the committed dose equivalent to any individual organ or tissue other than lens of the eye of 50 rems (0.5 Sv)

B. Annual limits to lens of the eye, to the skin, and to the extremities. which are

1. An eye dose equivalent of 15 rems (0.15 Sv), and
2. A shallow-dose equivalent of 50 rems (0.50 Sv) to the skin or to any extremity.

C. Annual limit to minors is 10 percent of that for adult workers.

II. Members of the Public

A. The total effective dose equivalent does not exceed 0.1 rem (1 mSv) per year (exclusive of dose from sanitary sewerage).

B. Dose in any unrestricted area from external source does not exceed 0.002 rem (0.02 mSv) in any one hour,

C. May apply for NRC authorization for an annual dose 0.5 rem (5 mSv).

(3) Effects of acute doses. The probable early effects of acute whole-body radiation dosages are summarized by Lamarsh in Table 2-5 (Lamarsh 1983).

(4) Carcinogenic effects. Delayed effects can be the result of an acute or chronic overexposure. Carcinogenic effects of radiation on the bone marrow, breast, thyroid gland, lung, stomach, colon, ovary, and other organs reported for the A-bomb survivors of Hiroshima and Nagasaki are similar to findings reported for other irradiated human populations. With few exceptions, however, the effects have been observed only at relatively high doses and dose rates. Studies of populations chronically exposed to low-level radiation, such as those residing in regions of elevated natural background radiation, have not shown consistent evidence of an associated increase in the risk of cancer.

(5) Genetic effects and life shortening. Ionizing radiation damages the genetic material in reproductive cells and results in mutations that are transmitted from generation to generation. However, genetic effects of radiation exposure in man have not been demonstrated at

the present time. Radiation has been found to be mutagenic in all organisms studied so far, and there is no reason to suppose that humans are exempt from radiation's mutagenic effects. Life shortening by increasing the rate of physiological aging is another effect that has been demonstrated in animals but not in humans. Detectable injury of the lens of the eye can result from a dose of as low as 1 Gy, depending on the dose rate and length of exposure time (LET) of the radiation. However, the threshold for a vision-impairing cataract under conditions of highly protracted exposure is thought to be no less than 8 Sv. This dose exceeds the amount of radiation that can be accumulated by the lens through occupational exposure to irradiation under normal working conditions and greatly exceeds that which is likely to be accumulated by a member of the general population through other types of exposure.

(6) In utero exposure effects. Children in utero are extremely susceptible to the effects from radiation exposure. Thus, a female worker who becomes pregnant should immediately notify her employers and remove herself from any potentially harmful situations.

(7) Possibility of new standards. There exists the possibility of modifications of the standards for the protection of human health due to new data gathered from the former Soviet Union. Preliminary, unreviewed data from the chronic internal and external exposures to beta-gamma radiation by whole populations affected by discharges from the Chelyabinsk complex, in contrast to the acute, neutron-gamma external exposure of the Japanese population, would indicate lower responses by a factor of 3 to 5. In addition, new interpretations of Japanese data have recently been formulated that may develop into new standards .

(8) Shielding requirements. Most external radiation exposures result from being unprotected or underprotected from the ionizing radiation. The proper amount of shielding can be determined by a trained health physicist and should be used at all times.

(a) Alpha shielding. Alpha particles are a unique type of radiation because they travel such short distances. The dead outer layer of skin is thick enough to absorb external alpha radiations. They are dangerous because, if they were to be ingested, inhaled, or absorbed by the skin, all of their energy would be deposited in living tissue in a localized region of the body, which might lead to cancer.

Table 2-4
Units for Health Physics

Concept	Special Unit SI Unit	Symbol	Definition	Conversion
Activity	Curie	Ci	$3.7 \times 10^{10} \text{ dps}^1$	$1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$
	Becquerel	Bq	1 dps^1	$1 \text{ Bq} = 2.7 \times 10^{-11} \text{ Ci}$
Exposure	Roentgen or charge/mass Air	R	$2.58 \times 10^{-4} \text{ C/kg air}^1$	$1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg air}^1$
	Charge/mass air ¹	C/kg ¹	1 Coulomb/kg air	$1 \text{ C/kg} = 3,876 \text{ R}^1$
Absorbed Dose	Energy/mass matter	rad	100 erg/g or $0.01 \text{ joule/kg matter}$	$1 \text{ rad} = 0.01 \text{ Gy}$
	Gray	Gy	$1 \text{ joule/kg matter}$	$1 \text{ Gy} = 100 \text{ rad}$
Dose	Roentgen	rem	$(\text{Abs. dose}) (Q)^1 \text{ or}$	$1 \text{ rem} = 0.01 \text{ Sv}$
Equivalent	Equivalent man		$0.01 \text{ joule (Q)/kg matter}$	
	Sievert	Sv	$1 \text{ joule (Q)}^1/\text{kg matter}$	$1 \text{ Sv} = 100 \text{ rem}$
Effective	Roentgen	rem	$(\text{Abs. dose}) (Q)(W^T)^1 \text{ or}$	$1 \text{ rem} = 0.01 \text{ Sv}$
Dose Equivalent	Equivalent man		$0.01 \text{ joule (Q)}(LW^T)/\text{kg matter}$	
	Sievert	Sv	$1 \text{ joule (Q)}(W^T)^1/\text{kg matter}$	$1 \text{ Sv} = 100 \text{ rem}$

¹dps = disintegration per second; C = coulomb; Q = quality factor; W^T = organ weighting factor.

²There is no SI unit for exposure. Exposure is still expressed in Roentgens or in C/kg of air exposed.

Table 2-5
Probable Early Effects of Acute Whole-Body Radiation
Doses^{1,2}

Acute dose (rems)	Probable Observed Effect
5 to 75	Chromosomal aberrations and temporary depression of white blood cell levels in some individuals. No other observable effects.
75 to 200	Vomiting in 5 to 50 percent of exposed individuals within a few hours, with fatigue and loss of appetite. Moderate blood changes. Recovery within a few weeks for most symptoms.
200 to 600	For doses of 300 rems or more, all exposed individuals will exhibit vomiting within 2 hours or less. Severe blood changes, with hemorrhage and increased susceptibility to infection, particularly at the higher doses. Loss of hair after 2 weeks of doses over 300 rems. Recovery from 1 month to a year for most individuals at the lower end of the dose range; only 20 percent survive at the upper end of the range.
600 to 1,000	Vomiting within 1 hour. Severe blood changes. hemorrhage, infection, and loss of hair. From 80 to 100 percent of exposed individuals will succumb within 2 months; those who survive will be convalescent over a long period.

¹The whole-body doses given in this table are those measured in soft tissue near the body surface; because of energy absorption in the body, the interior (or vertical midline) doses, which are sometimes quoted, are about 70 percent of the values in the table.

²Lamarsh (1983).

(b) Beta, gamma, and neutron shielding. Beta rays can easily be stopped by a few centimeters of plastic. However, when stopped by high-atomic number (Z) shielding, beta rays produce Bremsstrahlung x-rays, which can be highly penetrating. This effect is minimized by first using a low atomic number shield, such as plastic, to stop the beta rays, and then a high atomic numbered material, such as lead, to reduce the x-ray intensity to an acceptable level. X-rays and gamma rays can also be effectively attenuated by high atomic numbered lead, iron, and concrete. Neutrons can be effectively shielded by low Z materials such as water or paraffin.

2-2. Radioactive Waste Definitions

a. Low-level radioactive waste.

(1) Legal definition. As given in the Low-Level Radioactive Waste Policy Act, Public Law 96-573, low-level radioactive waste is defined as

“...radioactive waste not classified as high-level radioactive waste, transuranic waste, spent nuclear fuel, or by-product materials as defined in Section 11 e(2) of the Atomic Energy Act (uranium and thorium tailings and wastes).”

Thus, (a) high-level radioactive waste, (b) transuranic waste, (c) spent nuclear fuel, and (d) by-product materials need to be defined.

(a) High-level radioactive waste means the highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations. High-level radioactive waste also includes other highly radioactive material that the Commission, consistent with existing law, determines by rule requires permanent isolation.

(b) Transuranic waste means waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes, with half-lives greater than 20 years, per gram of waste, except for:

.High-level radioactive waste.

- Wastes that the Department has determined, with the concurrence of the Administrator, do not need the degree of isolation required by this part.
- Wastes that the Commission has approved for disposal on a case-by-case basis in accordance with 10 CFR 61.

(c) Spent nuclear fuel is fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing.

(d) By-product material means:

- Any radioactive material (except special nuclear material) yielded in or made radioactive by exposure to the radiation incident to the process of producing or utilizing special nuclear material.
- Tailings or wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content.

(2) Regulatory definition. In 10 CFR 61, "Licensing Requirements for Land Disposal of Radioactive Waste" (low-level waste only), the definition states that "waste means those low-level radioactive wastes containing source, special nuclear, or by-product materials that are acceptable for disposal in a land disposal facility. For purposes of this definition, low-level waste has the same meaning as in the LLRWPA." Thus, source material and special nuclear material now need to be defined as given in 10 CFR 20.

"Source material" means--

(a) Uranium or thorium or any combination of uranium and thorium in any physical or chemical form; or

(b) Ores that contain, by weight, one-twentieth of 1 percent (0.05 percent), or more, of uranium, thorium, or any combination of uranium and thorium. Source material does not include special nuclear material.

"Special nuclear material" means--

(a) Plutonium, uranium-233, uranium enriched in the isotope 233 or in the isotope 235, and any other material that the Commission, pursuant to the provisions of section 51 of the Act, determines to be special nuclear material, but does not include source material; or

(b) Any material artificially enriched by any of the foregoing (does not include source material).

(3) Class designations. Once a radioactive waste has been determined to be low-level, it must be classified as Class A, B, or C. Low-level wastes are divided by 10 CFR 61 into these three classes based upon their long-lived and short-lived constituents. Numerical limits for Class A, B, and C low-level wastes are determined by the concentrations of long-lived radionuclides, as

shown in Table 2-6, and concentrations of short-lived radionuclides, shown in Table 2-7.

Table 2-6
Long-Lived Material

Radionuclide	Concentration
C-14	8 Ci/m ³
C-14 in activated metal	80 Ci/m ³
Ni-59 in activated metal	220 Ci/m ³
Nb-94 in activated metal	0.2 Ci/m ³
Tc-99	3 Ci/m ³
I-129	0.08 Ci/m ³
Alpha-emitting, transuranic nuclides with half-life >5 yr	100 nCi/g
Pu-241	3,500 nCi/g
Cm-242	20,000 nCi/g

Table 2-7
Short-Lived Material

Radionuclide	Concentration, Ci/m ³		
	Column 1	Column 2	Column 3
Total of all nuclides with half-life <5 yr ¹	700		
H-3 ¹	40		
Co-60 ¹	700		
Ni-63	3.5	70	700
Ni-63 in activated metal	35	700	7,000
Sr-90	0.04	150	7,000
Cs-137	1	44	4,600

¹There are no limits established for these radionuclides in Class B or C wastes. Practical considerations such as the effects of external radiation and internal heat generation on transportation, handling, and disposal will limit the concentrations for these wastes. These wastes shall be Class B unless the concentrations of other nuclides in the table determine the waste to be Class C independent of these nuclides.

(a) Class A Definition. Class A wastes are defined as waste that does not contain sufficient amounts of radionuclides to be of concern with respect to migration of radionuclides, long-term active maintenance, and potential exposures to intruders, and that tends to be stable, such as ordinary trash wastes.

(b) Class B definition. Because of their higher activity level and greater hazard potential, Class B wastes must meet more rigorous disposal requirements for waste form stability than do Class A wastes.

(c) Class C definition. Class C wastes have even greater activity, so they must also meet more rigorous requirements for waste form, and have further restrictions on their burial, such as a minimum depth of 5 m below the top surface of the cover, or with barriers designed to protect against inadvertent intrusion for at least 500 years.

(d) Greater-than-Class C definition. Wastes that do not meet the requirements of Class C for near-surface disposal require waste forms and disposal methods that are different and in general more stringent than those specified for Class C waste. Wastes that are considered greater than Class C wastes are now treated as high-level wastes and, thus, do not fall under the scope of this EM.

(e) Use of Table 2-6 for class designations. The following are the guidelines for using Tables 2-6 and 2-7 to identify the class designation of low-level radioactive waste. If a waste contains only those radionuclides listed in Table 2-6, it is classified as follows:

If the concentration does not exceed 0.1 of the value in Table 2-6, it is Class A waste.

If the concentration exceeds 0.1 of the value, but is less than the value in Table 2-6, it is Class C waste.

If it exceeds the concentration in Table 2-6, the waste is not generally acceptable for near-surface disposal.

For mixtures of long-lived Table 2-6 wastes, the standard sum of the ratios of the concentration of each of the contained wastes to the concentrations in the table shall not exceed the limits indicated above.

(f) Use of Table 2-7 for class designations. If the wastes do not contain any of the long-lived radionuclides listed in Table 2-6, then they are classified by the short-lived radionuclides in Table 2-7, as follows:

If the concentrations do not exceed those listed in Column 1, the waste is Class A.

If the concentrations are greater than those in Column 1, but equal to or less than those in Column 2, the waste is Class B.

If the concentration is greater than the values in Column 2 and equal to or less than those in Column 3, the waste is Class C.

If the concentrations are greater than those in Column 3, the waste is not generally acceptable for near-surface disposal.

If the wastes contain a mixture of Table 2-7 short-lived radionuclides, the sum of the fractions of the concentration of each of the contained wastes to the concentrations in the table shall not exceed the limits indicated above.

(g) Mixtures of Table 2-6 and 2-7 wastes. If the waste contains a mixture of Table 2-6 and Table 2-7 wastes, then the following applies.

If the waste is classified as Class A by Table 2-6, the classification shall be determined by Table 2-7.

If the waste is classified as Class C by Table 2-6, it shall be classified as Class C, provided the concentration of Table 2-7 wastes does not exceed the values in Column 3.

(h) Designation for waste not included in Table 2-6 or 2-7. If the radioactive waste contains only radionuclides not listed in either Table 2.6 or 2.7, then the waste shall be classified as Class A.

(i) Example of class determination. An example of the classification of a waste follows: suppose a waste contained 0.2 Ci/m³ of ¹⁴C, 0.002 Ci/m³ of ⁹⁰Sr, and 10 Ci/m³ of ¹³⁷Cs. By Table 2-6, the waste is classified as Class A because 0.2 Ci/m³ of carbon-14 is less than 0.1 of the carbon-14 limit given in Table 2-6. Thus, the determination falls on the Table 2-7 radionuclides.

The comparison concentrations from Column 1 in Table 2-7 are 0.04 Ci/m³ and 1 Ci/m³, respectively, for ⁹⁰Sr and ¹³⁷Cs. Thus.

$$\frac{0.002}{0.04} + \frac{10}{1} > 1 \quad (2-6)$$

and the sum of fractions of the standards in column 1 are greater than 1 and, therefore, the mixture is greater than class A. The standards from Column 2 are 150 Ci/m³ and 44 Ci/m³, respectively. Thus, the sum of the fractions is less than 1.

$$\frac{0.002}{150} + \frac{10}{44} < 1 \quad (2-7)$$

Thus, the waste would be classified as Class B.

b. Below regulatory concern (BRC) waste.

(1) BRC concept. Many believe that there should be a minimum level of radioactivity needed for waste to be considered low-level radioactive waste for regulatory purposes. The BRC concept defines radiation exposures associated with radioactive waste disposal that are so low that regulation with respect to radiation hazard is not warranted. BRC levels are dependent upon the waste stream, disposal technologies available, and the potential for exposure. BRC levels are designated by conscious decision at values below which the benefits of society outweigh the risk.

(2) Advantages of a BRC level. Since many waste streams are treated as low-level radioactive waste streams because of trace or even only suspected levels of man-made radioactivity, the establishment of a BRC level would allow such wastes to be disposed of in a less restrictive manner, at substantial cost savings, and with minimal risk to the public. A BRC level might also allow some waste streams currently classified as mixed to become hazardous waste streams. However, after the furor of the Nuclear Regulatory Commission (NRC) attempt to promulgate a BRC rule, Congress has forbidden any such rulemaking.

c. De minimis waste.

(1) De minimis definition. A *de minimis* dose defines a range of exposure below which health physicists think no quantifiable risks exist. *De minimis* means the least and is an abbreviation for *de minimis non curat lex*, generally translated “the law does not pay attention to the trivial.” Unlike BRC levels, *de minimis* levels are generally defined solely in terms of probable mortality for exposed individuals, exclusive of the size of the exposed population and the total number of expected mortalities.

(2) Advantages of de minimis level. The NRC has set *de minimis* levels (0.05 microcuries per gram) for

tritium and ¹⁴C in liquid scintillation fluids and animal carcasses so that they may be disposed of without regard to their radioactivity. If *de minimis* levels could be established for other radionuclides in other wastes, the volume of low-level waste needing disposal would be reduced which would decrease the need for multiple sites, extend operating life of existing sites, result in significant cost savings to generators, and permit resources to be reallocated to better serve our society.

d. Naturally occurring and accelerator-produced radioactive materials (NORM/NARM).

(1) NORM and NARM definitions. Two broad categories of radionuclides not covered under the Atomic Energy Act (AEA) are naturally occurring radionuclides of insufficient concentration to be considered source material and accelerator-produced radionuclides. Materials containing accelerator-produced nuclides are commonly referred to as NARM wastes. NARM are not regulated under the AEA or any other Federal regulation. At the State level, regulation is nonuniform. Recommended regulations for NARM and discrete NORM are similar to those currently required for by-product materials. These wastes are generated from particle accelerators and from naturally occurring radioisotopes, principally uranium, thorium, and radium. Naturally occurring radioactive material (NORM) is the radioactive material in its natural physical state and does not include by-product, special nuclear, or source material. NORM is a subset of NARM.

(2) Discrete wastes. NORM wastes can be further classified as discrete or diffuse. Discrete NORM wastes pertain to small-volume, high-specific-activity sources which might include Radium-sealed sources, certain water treatment ion exchange resins, and certain oil and pipe scale.

(3) Diffuse wastes. Diffuse NORM pertains to large-volume, low-specific-activity sources which were created by processing or technologically enhancing materials originally found in nature that otherwise were in small concentrations of naturally occurring radioactive isotopes. Diffuse NORM may be a product of mineral extraction and mill tailings, oil and gas extraction, coal fly ash and bottom ash creation, phosphate mining, water treatment and some uranium mining residues. According to an Environmental Protection Agency (EPA) report entitled “Low-Level and NARM Radioactive Wastes: Draft Environmental Impact Statement for Proposed Rules, Background Information Document,” living next to these sources can produce a 10⁻⁴ to 10⁻¹

excess lifetime cancer risk (EPA 1988). According to the NRC's 10 CFR 20, Appendix B, Thorium-232 derived air concentrations (DACS) are five times more restrictive than Plutonium-239 DACS.

(4) High concentration NARM wastes. The higher concentration NARM wastes are similar to LLRW. They are either disposed of as such or stored onsite until they decay sufficiently. If the concentration of uranium or thorium exceeds 0.05 percent by weight, the waste is classified as a source material. The lower activity diffuse wastes such as the mine overburden have very low concentrations of radionuclides but are produced in large volumes. Thus, disposal in an LLRW facility is impractical.

2-3. Hazardous Waste Definitions

a. RCRA definition. Hazardous waste is defined in Section 1004(5) of the Resource Conservation and Recovery Act (RCRA) as:

... a solid waste, or combination of solid waste, which because of its quantity, concentration, or physical, chemical, or infectious attributes, may: (A) cause, or significantly contribute to, an increase in mortality or an increase in serious irreversible, or incapacitating reversible, illness or (B) pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed.

b. CERCLA definition. The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 (Section 101(14)) defines "hazardous substances" as

- (A) Any substance designated pursuant to Section 311 (b)(2)(A) of the Federal Water Pollution Control Act.
- (B) Any element, compound, mixture, solution, or substance designated pursuant to Section 102 of this Act.
- (C) Any hazardous waste having the characteristics identified under or listed pursuant to Section 3001 of the Solid Waste Disposal Act (SWDA) (but not including any waste the regulation of which under the SWDA has been suspended by Act of Congress).

(D) Any toxic pollutant listed under Section 307(a) of the Federal Water Pollution Control Act.

(E) Any hazardous air pollutant listed under Section 112 of the Clean Air Act.

(F) Any imminently hazardous chemical, substance, or mixture with respect to which the Administrator has taken action pursuant to Section 7 of the TSCA.

c. Listed or characteristic wastes. A hazardous waste can be a listed waste and/or a characteristic waste. Listed wastes are wastes that have been listed by EPA in 40 CFR 261 Subpart D and have not been specifically delisted. Characteristic wastes are wastes that exhibit any of the four characteristics for identifying hazardous waste in 40 CFR 261 Subpart C which are ignitability, corrosivity, reactivity, and toxicity characteristic leaching procedure (TCLP) toxicity. The procedures or tests to determine if a waste exhibits these characteristics are discussed in 40 CFR 261, Subpart C.

d. Classes of hazardous wastes. The major classes of hazardous wastes are volatile organic compounds (VOCs), semivolatile organic compounds (SVOCs), and metals. Hazardous materials that may contact radioactive material and end up as a mixed waste include cleaning solutions, solvents, oils, lead, and cadmium. The deregulation of liquid scintillation fluids in 1981 (10 CFR 20.306) eliminated a major contributor to the mixed waste stream.

2-4. Mixed Waste Definitions

a. Definition of mixed waste. Mixed wastes are those wastes that contain radioactive materials at concentrations equivalent to low-level wastes and also contain hazardous waste materials (listed and/or characteristic) and are subsequently subject to regulation by both the EPA and the NRC. Joint NRC and EPA guidance issued on January 8, 1987 titled "Guidance on the Definition and Identification of Commercial Mixed Low-Level Radioactive and Hazardous Waste and Answers to Anticipated Questions," contains the following definition (NRC-EPA 1987):

Mixed Low-Level Radioactive and Hazardous Waste (Mixed LLRW) is defined as waste that satisfies the definition of low-level radioactive waste (LLRW) in the Low-Level Radioactive Waste

Policy Amendments Act of 1985 (LLRWPA) and contains hazardous waste that either (1) is listed as a hazardous waste in Subpart D of 40 CFR Part 261 or (2) causes the LLRW to exhibit any of the hazardous waste characteristics identified in Subpart C of 40 CFR Part 261.

b. Regulatory oversight of mixed waste

(1) Hazard potential. The applicable laws and regulations leading to this dual control by two separate federal agencies will be discussed in more detail in the next section of this manual. 10 CFR 20.2007 requires generators of radioactive waste to also comply with any other regulations governing any other toxic or hazardous properties of radioactive wastes. This is important since the half-life of most of the elements in LLRW can be measured in hours or days; of others, in decades or longer. As a result, almost all LLRW decays to harmless levels relatively quickly. After about 300 years, it becomes only as radioactive as natural soil. By comparison, many other potentially hazardous, but nonradioactive, chemical wastes like lead, silver, arsenic, barium, cadmium, chromium, mercury, and selenium do not decay away. Their toxicity remains forever.

(2) Joint jurisdiction. Disposal of hazardous wastes is regulated by the Environmental Protection Agency under RCRA while radioactive wastes are controlled by the NRC under the AEA. If the host state is an agreement state or RCRA approved state, then it may have its own definition of hazardous wastes. It has been necessary to establish consistent dual rules by agreement between agencies. The EPA and NRC provide a formal procedure by which one can decide whether a certain material is mixed waste. It is estimated that only a few percent of low-level wastes are in the category of mixed waste.

(3) Scintillation fluids. Liquid scintillation fluids are used in medical testing to measure radioactive isotopes. Both NRC and EPA allow scintillation fluids to be incinerated. Also, an EPA permit is not needed if the fluid is burned as fuel additive. According to the profile, a significant portion of commercially generated mixed waste may be treated using existing commercial treatment facilities. Because these scintillation liquids are no longer regulated by the NRC, they can be treated according to their composition and chemical hazard.